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AF Research Laboratory / Materials and Manufacturing Directorate

Metals, Ceramics, and NDE Division

Development of Super-high Strength Aluminum Alloys for Cryogenic Applications

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AFRL Contract F04611-02-C-0014
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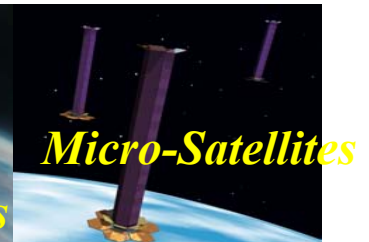
Background



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- Few years ago, the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program has started in the USA that is focused on developing measurable, affordable and goal directed aerospace technologies.
- The IHPRIPT goal is to double space and missile propulsion capability while significantly decreasing manufacturing and maintenance costs by 2010.
- In particular, it is expected to improve thrust to weight of cryogenic liquid rocket engines by 100%.





Space Shuttle Main Engine



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Propellants:

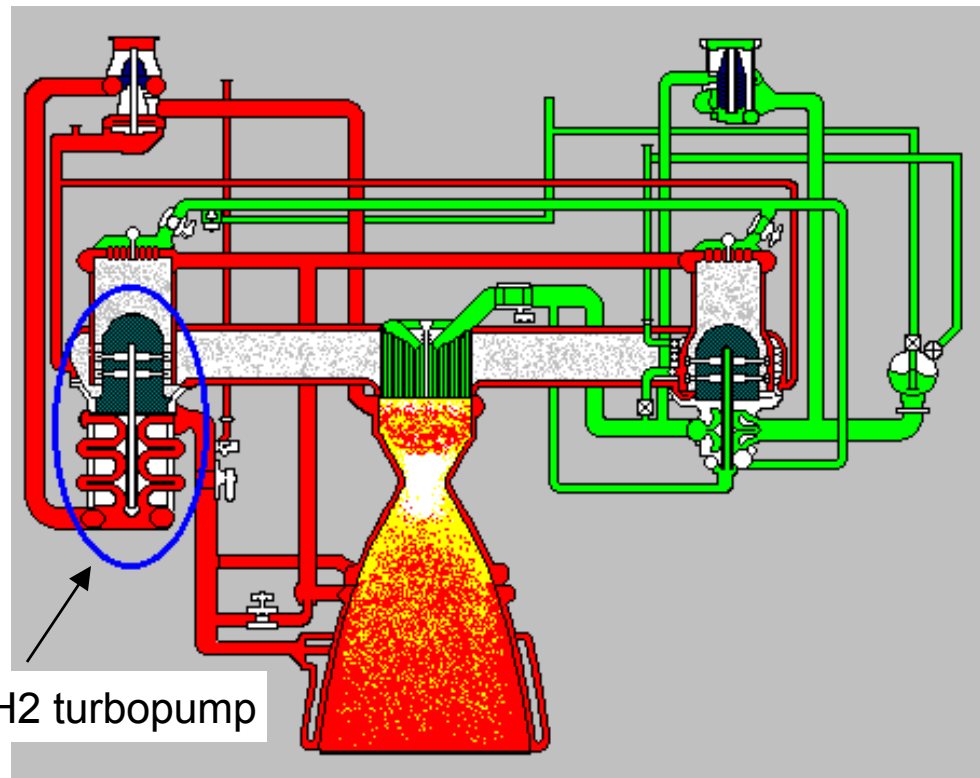
LOX/H₂

Thrust:

2160 kN

Weight:

3350 kg



LH2 turbopump



Background



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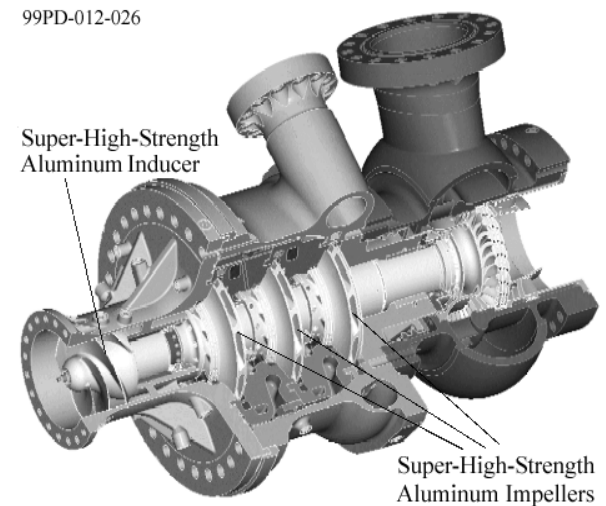
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- LH₂ three stage turbopump consists of three Ti-5Al-2.5Sn ELI impellers.
- Maximum tip speed of impellers required to produce maximum fuel pressure in the combustion chamber and maximum thrust is limited by specific strength.

Alpha titanium alloy Ti-5Al-2.5Sn ELI has excellent properties at cryogenic temperatures; however it is (a) expensive and (b) prone to hydrogen embrittlement.

Aluminum alloys are (a) much less expensive, (b) ~ 1.6 times lighter, (c) much less sensitive to hydrogen environment.

It would be beneficial to use an Al alloy instead of the Ti alloy.



IPD Fuel Turbopump
(Courtesy of Rocketdyne)



Property Requirements



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Properties of Ti-5Al-2.5Sn ELI alloy (density = 4.6 g/cm³)

- ♦ 25°C (RT): YS=760 MPa; UTS=840 MPa; El=15%
- ♦ -196°C (LN₂): YS=1100 MPa; UTS=1260 MPa; El=15%
- ♦ -253°C (LH₂): YS=1260 MPa; UTS=1420 MPa; El=13%

Al alloy (density = 2.8 g/cm³) to achieve similar specific strengths must have:

- ♦ 25°C (RT): YS=463 MPa; UTS=511 MPa (SS=182 kN m/kg)
- ♦ -196°C (LN₂): YS=670 MPa; UTS=767 MPa (SS=274 kN m/kg)
- ♦ -253°C (LH₂): YS=767 MPa; UTS=864 MPa (SS=308 kN m/kg)

Customer requirements for advanced Al alloy:

UTS ≥ 620 MPa at 25°C, ≥ 800 MPa at -196°C, ≥ 900 MPa at -253°C
El ≥ 7%



Commercial Aluminum Alloys



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Mechanical properties of commercial aluminum alloys at -253°C (-423°F)

Material	2024	5083	5456	6061	7075	X7106	356
YS, MPa	428-635	173-566	324-428	331-380	538-676	449-511	228-282
UTS MPa	621-725	497-669	497-587	449-538	697-759	600-669	324-393
EL (%)	13-23	10-40	6-17	20-32	6-15	14-25	2-9

- ☹ Required properties ($YS \geq 770 \text{ MPa}$, $UTS \geq 900 \text{ MPa}$) cannot be achieved
None of the currently available commercial Al alloys can provide specific strength equivalent to that of the Ti alloy



Goals



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➡ **Identify and develop aluminum based alloy for cryogenic rocket engine applications instead of currently used Ti-5Al-2.5Sn ELI alloy and other alloys**

Parts

Impellers

Pump Housing

Ducts and pipes

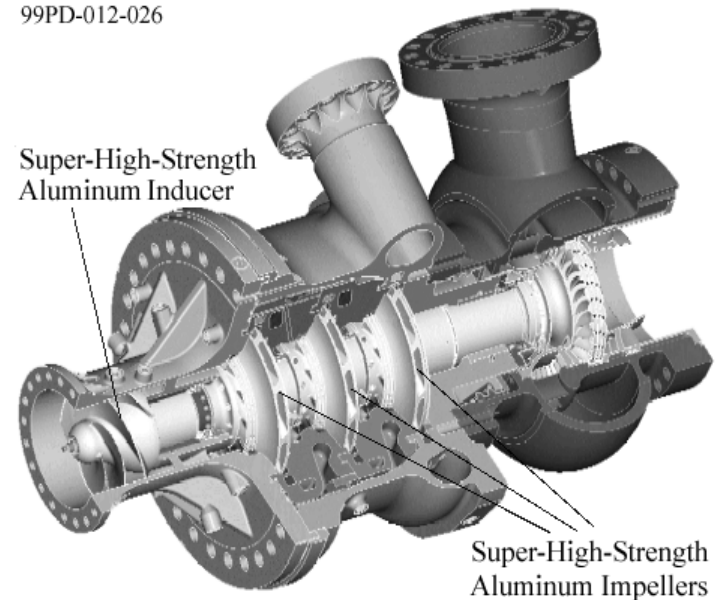
Processing

Forging

Casting

Extrusion

99PD-012-026



IPD Fuel Turbopump
(Courtesy of Rocketdyne)



Developmental Al Alloys



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Novel non-equilibrium processes

- **Rapidly solidified Al alloys**
- **Mechanically alloyed**
- **Amorphous, nanocrystalline, quasi-crystalline**
 - ☺ **Advantages**
 - ✓ Novel compositions and phases
 - ✓ Required properties may be achieved
 - ☹ **Disadvantages**
 - ✓ Expensive in development
 - ✓ Expensive in production
 - ✓ Desired properties can be lost during high-temperature processing



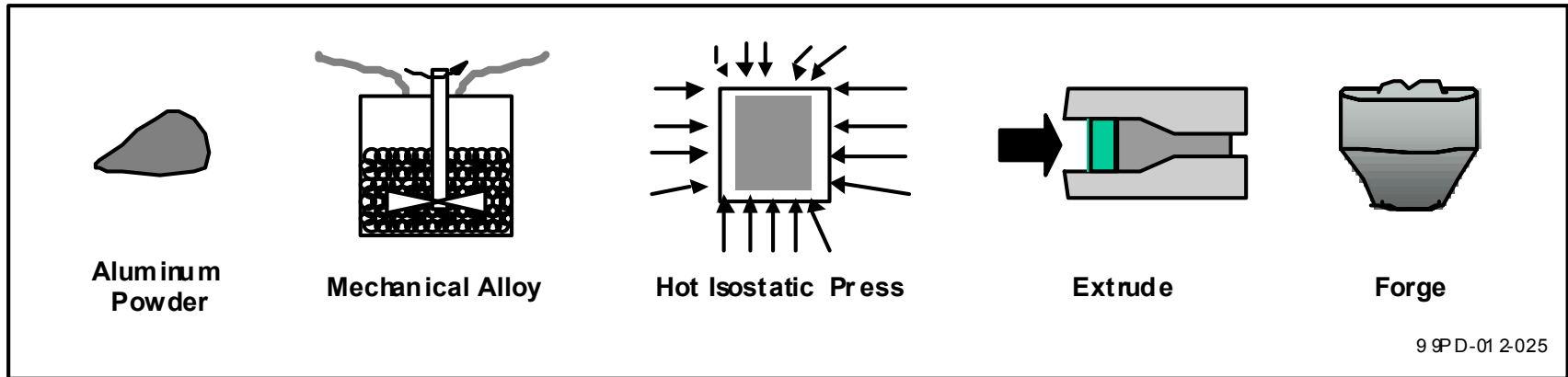
Recent Developments



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Nanophase Aluminum



Schematic of fabrication of nanophase aluminum alloys

Property levels of Al-7.5%Mg at LN₂:

YS=518 MPa (75.0 ksi), UTS=659 MPa (95.5 ksi), and El=4.9%

Dual Use Sci.&Technology Program (RPP, RSC, AFRL/WPAFB) started in 2000 to develop a second generation, higher strength NA alloy



Our Approach



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- ▶ Use conventional practice of casting, hot working, and heat treatment
- ▶ Try to achieve required properties through modifications of alloy composition and processing parameters of a 7XXX alloy.
- ▶ Modify the alloy composition to increase the volume fractions of precipitates (η' , Zn_2Mg) and dispersoids (L1_2 , Al_3Sc , etc.)
- ▶ Modify processing parameters to achieve required combination of strength and ductility by optimizing the number density of the precipitates and dispersoids and refining grain size
 - ▶ Main dispersoid formers are Sc and Zr; they also may improve both strength and ductility of Al alloys
 - Sc and Zr are precipitation-strengtheners, grain refiners, and recrystallization inhibitors for Al alloys.
 - Sc also improves stress corrosion resistance of Al alloys.
 - ▶ Cryogenic properties of 7XXX alloys modified with Sc and Zr have not been reported yet.



Experimental



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- Compositions of alloys investigated (in wt.%)
 - 7-12 Zn; 2.3-3.3 Mg; 1.2-2.5 Cu; 0.10-0.20 Zr; 0-0.5 Sc; up to 1.0 others; balance Al
 - Alloys with $\geq 8\%$ Zn showed very high strength, but almost zero ductility at cryogenic temperatures
- Compositions of the alloys presented in this report

Alloy #	Zn	Mg	Cu	Zr	Sc	Other	Al
SSA000	7.14	2.30	1.61	0.17	0	0.8	Bal.
SSA018	7.17	2.20	1.58	0.18	0.18	0.8	Bal.

- 75-mm diameter alloy billets were produced by DC casting
- Homogenization at 460°C up to 48 hours
- Extrusion at 400°C and 450°C with 16:1 extrusion ratio
- Forging at 400°C and 450°C with compression strain of 80%
- Heat treatment
- Tensile properties at 23°C and -196°C



Results

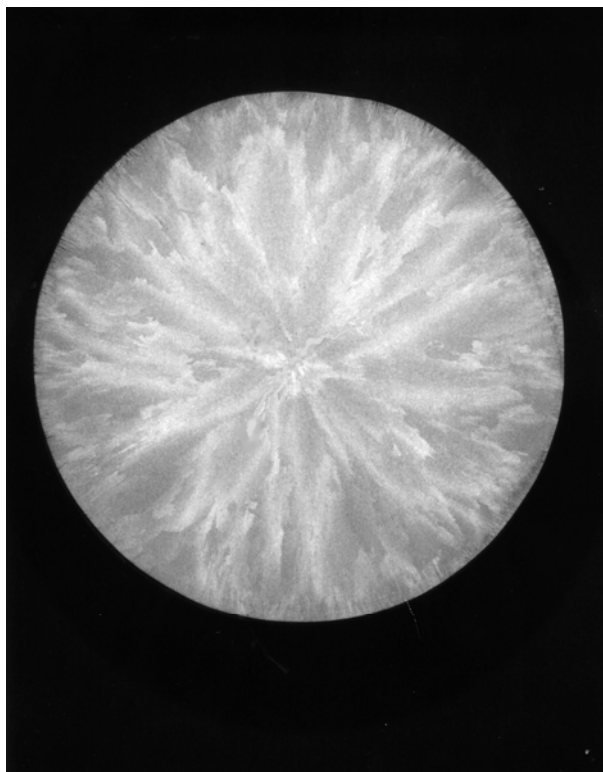


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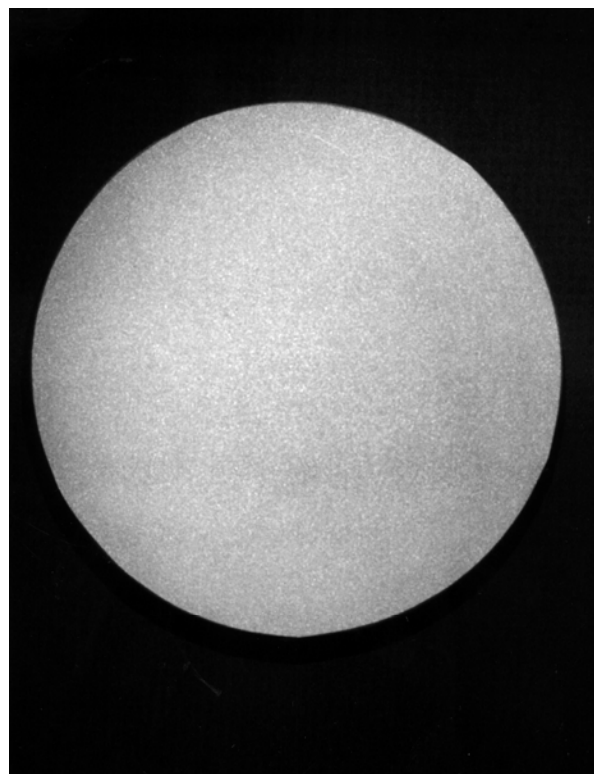
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Photo-macrographs of transverse cross-sections of continuously DC cast billets of SSA alloys.

0% Sc



0.18% Sc





Results



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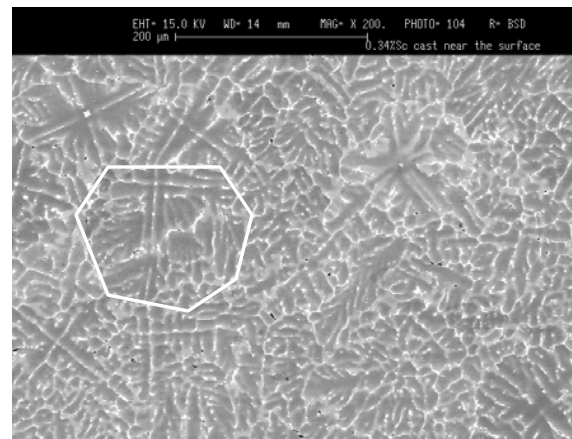
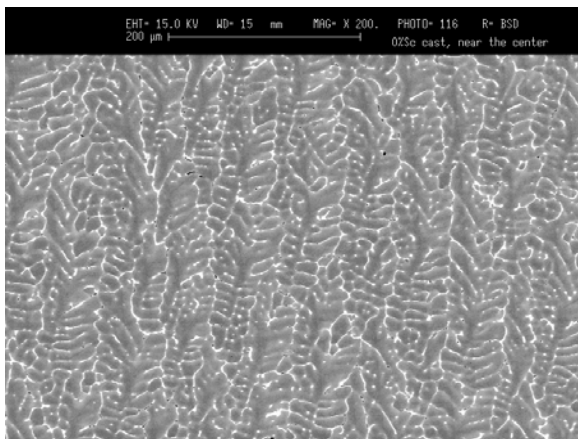
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SEM photomicrographs of of SSA cast alloys

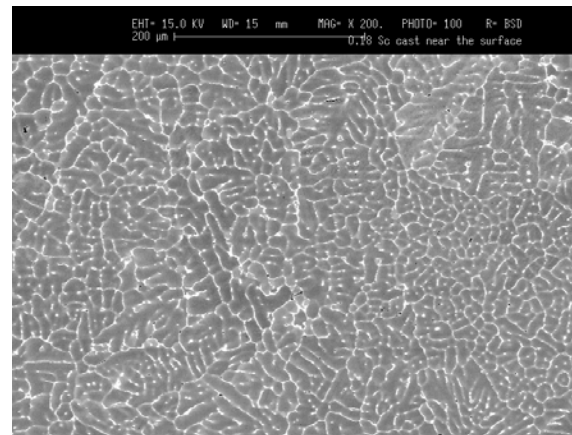
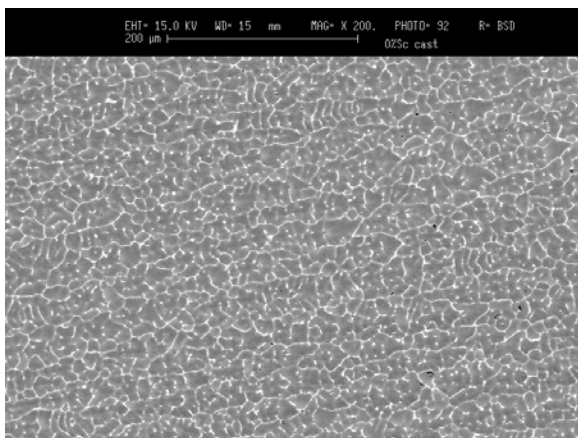
SSA000

SSA018

Longitudinal
cross-sections



Transverse
cross-sections





Properties of cast alloys

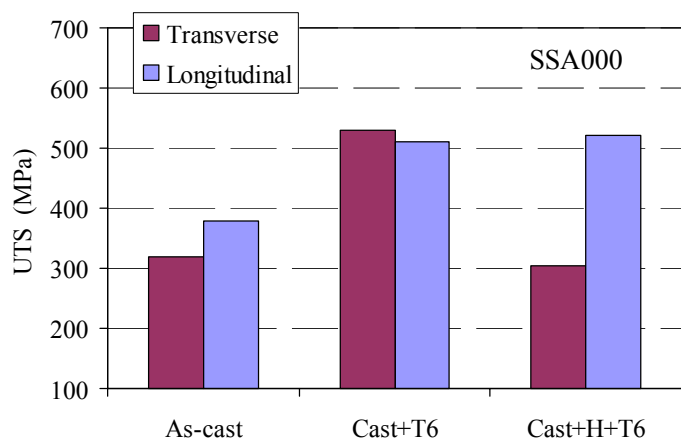


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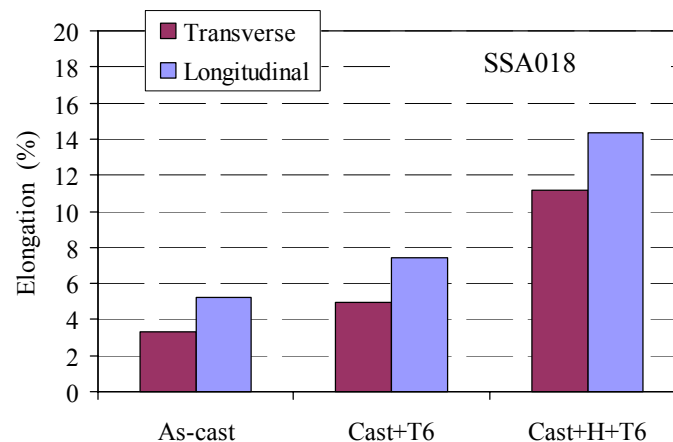
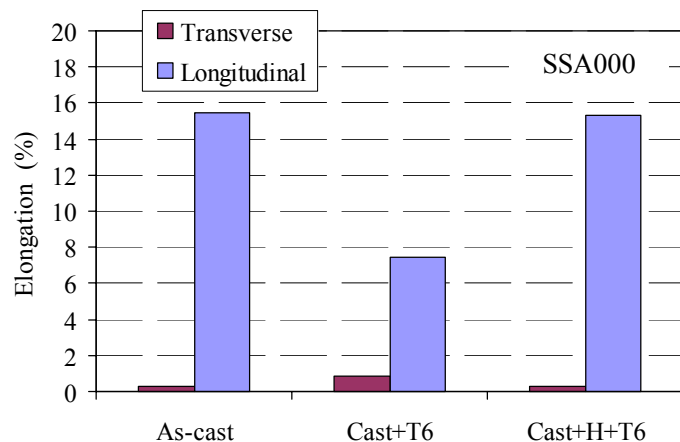
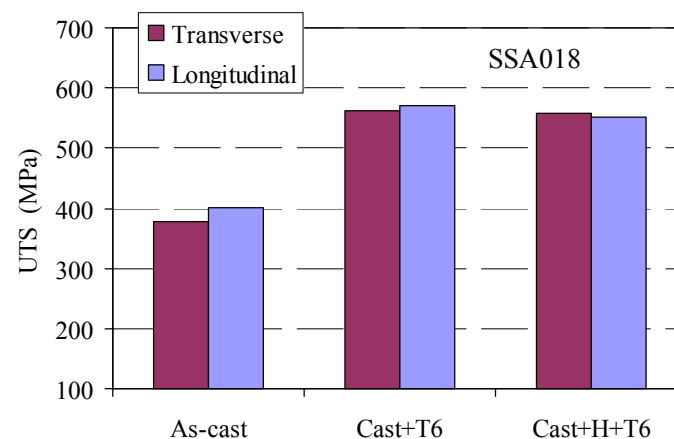
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Room temperature tensile properties of DC cast billets

0%Sc



0.18%Sc





Properties of cast alloys

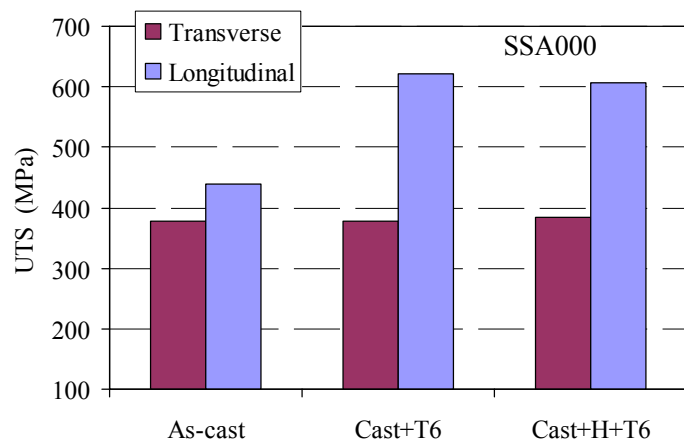


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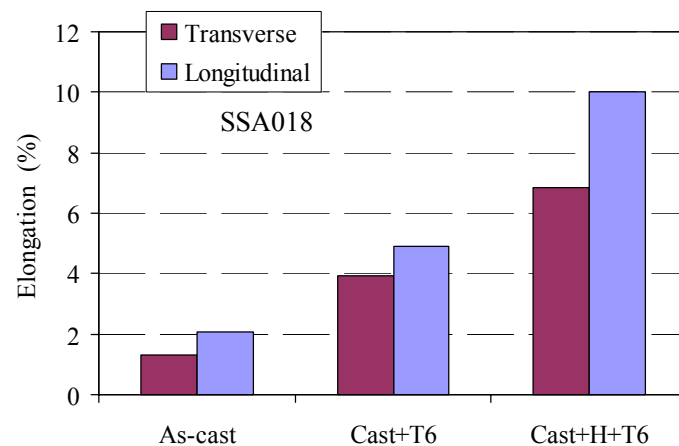
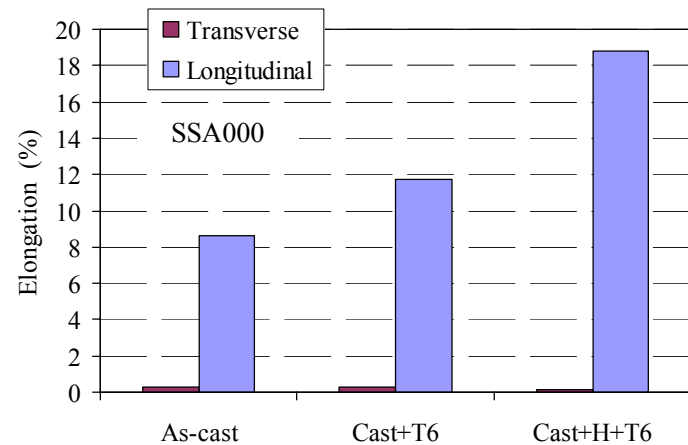
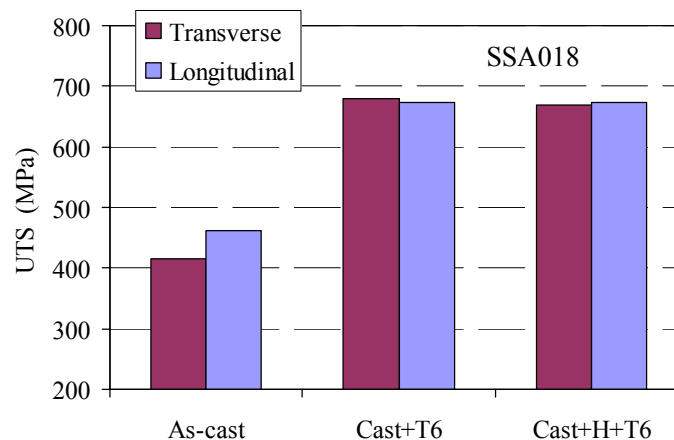
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Cryogenic (-196°C) tensile properties of DC cast billets

0% Sc



0.18% Sc





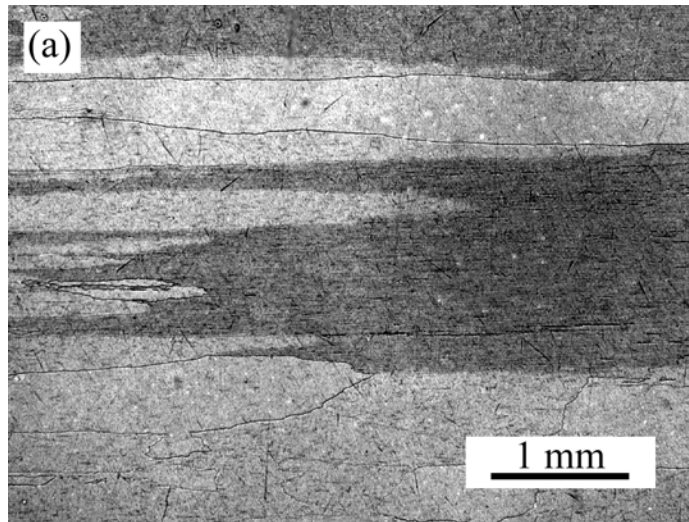
Extrusion



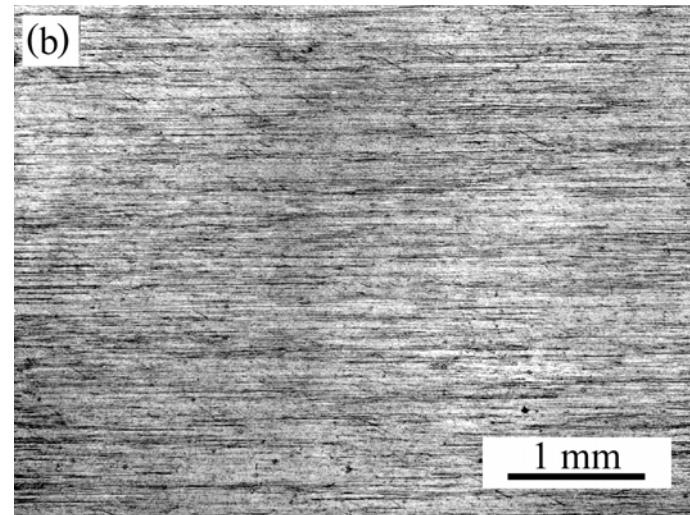
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Microstructure of extruded and heat treated specimens



0% Sc



0.18% Sc



Extrusion

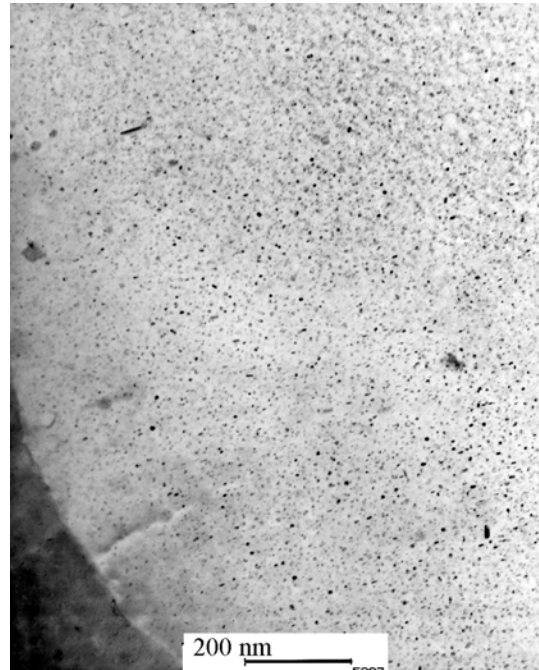


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TEM microstructure of aged specimens

120C for 19 h



0.18%Sc

$d = 5-20 \text{ nm}$

$n = 10^{22}-10^{23} \text{ m}^{-3}$



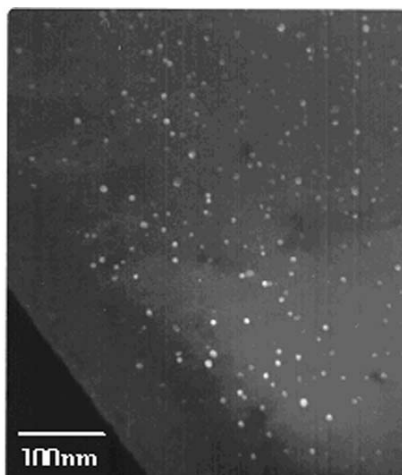
Microstructure



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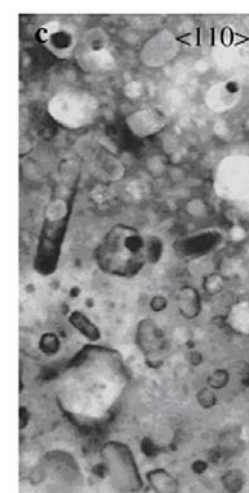
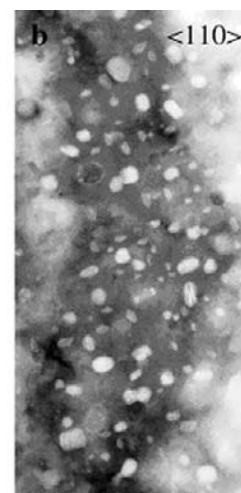
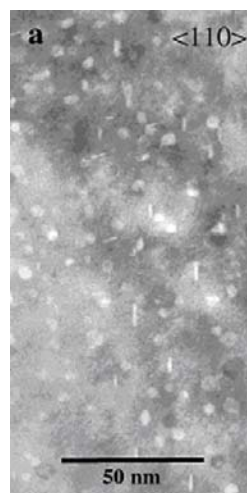
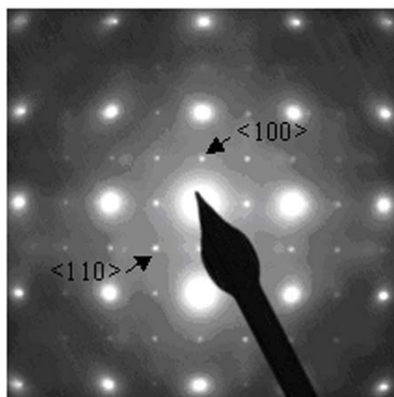
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Precipitations in a solution annealed and aged SSA018 alloy



Solution annealed and water quenched
($L1_2$ coherent particles)

M. Mills, Ohio State U.



Bright field TEM images for the 0.18%Sc alloy after aging for 1, 24 and 48 hours
(η $MgZn_2$ particles)



Extrusion

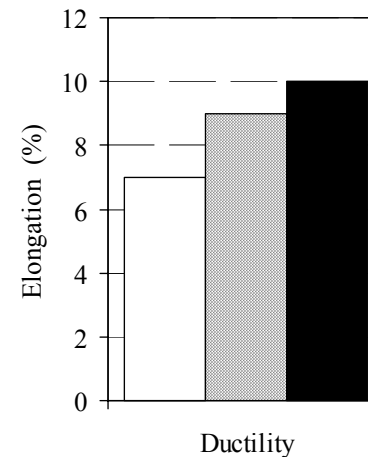
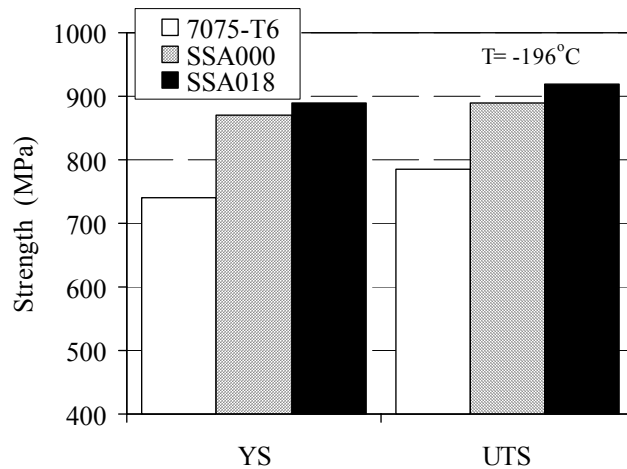
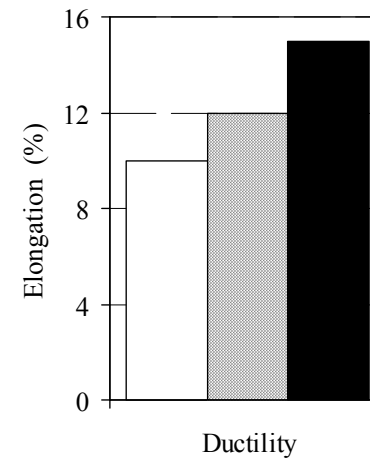
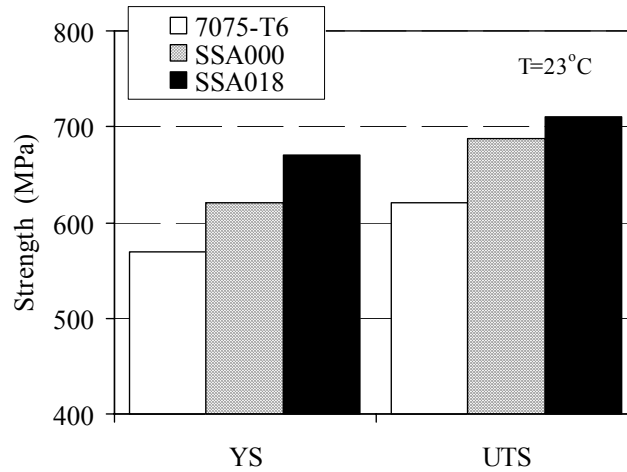


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Tensile properties of extruded alloys

(Extrusion at 400°C, 16:1)





Forging



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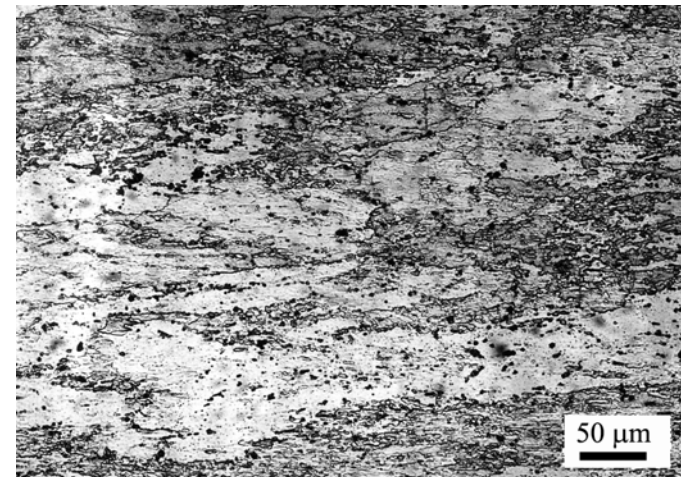
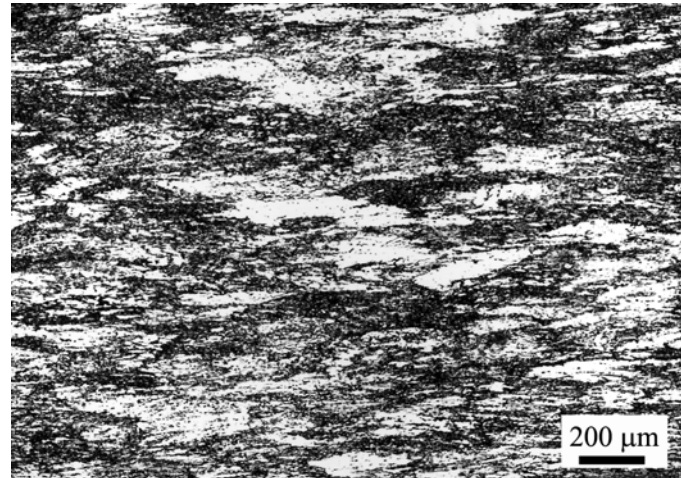
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SSA018

Microstructure of forging



164 mm diameter
28 mm height



Radial
direction →

↓
Direction of
Forging



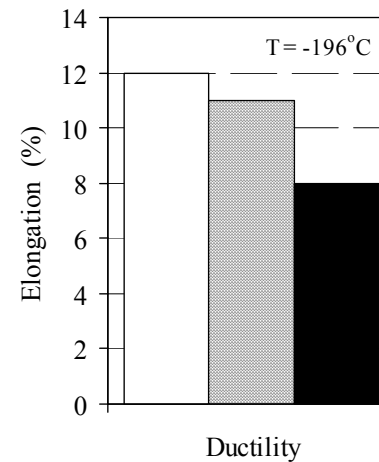
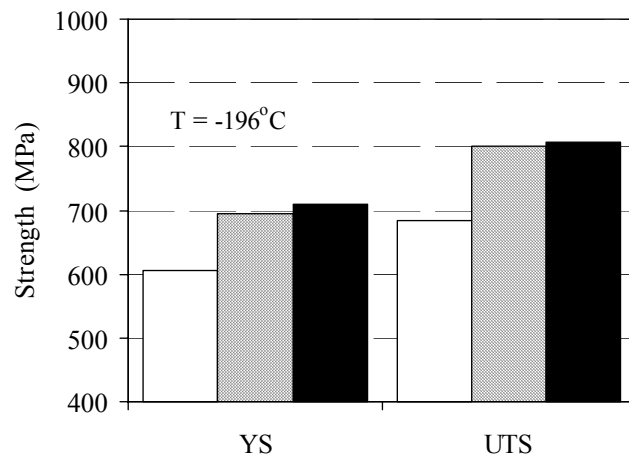
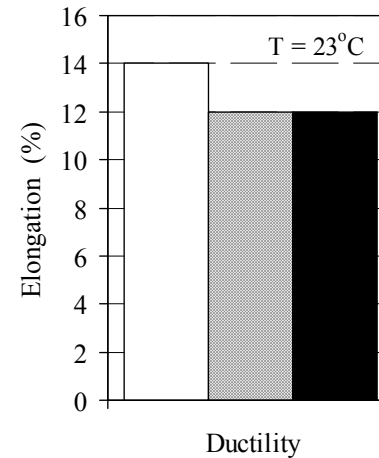
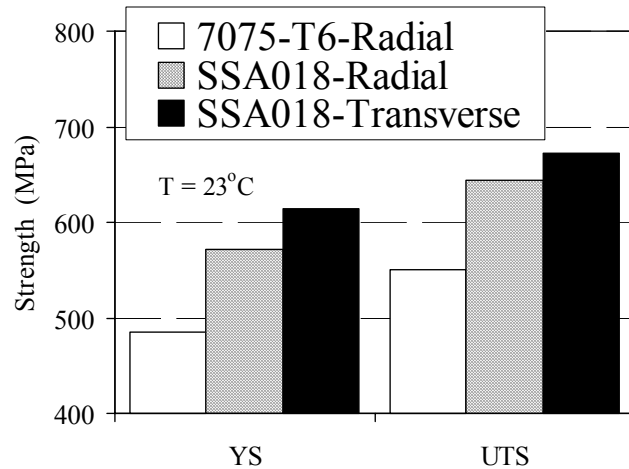
Forging



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Tensile properties of forging





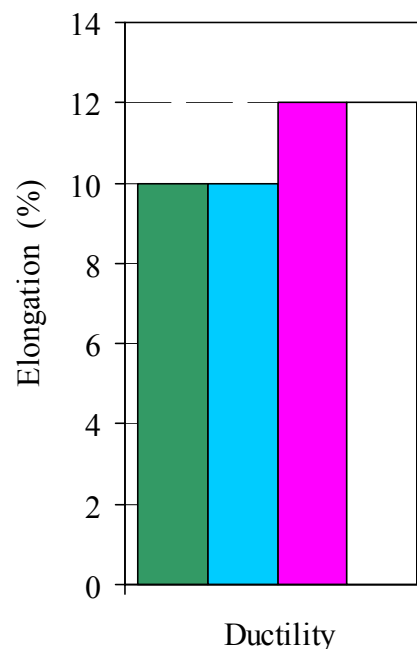
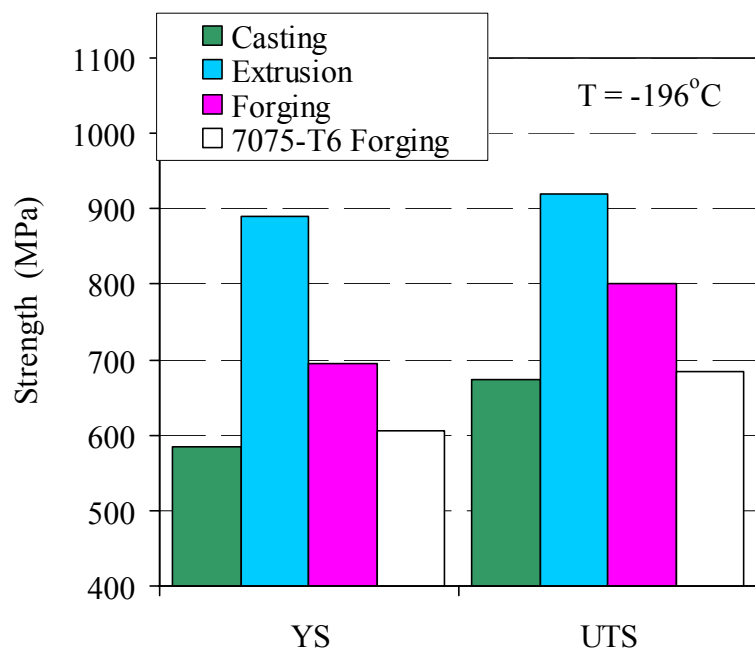
Cryogenic tensile properties (summary)



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Cryogenic properties of SSA018 alloy
in cast, extruded and forged conditions after T6 temper





Conclusion



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- Super-high strength cast and wrought Al alloys have been developed. The alloys belong to 7XXX series and contain increased amounts of dispersoid-forming (grain-refining) elements (Zr, Sc, Ti, Cr, Mn, etc.)
- The grain-refining elements refine microstructure of casting and retard recrystallization and grain growth during homogenization, hot working and solution treatment.
- The T6 tempered SSA018 alloy shows superior tensile strength at room and cryogenic temperatures, both in cast, extruded and forged conditions.
- High strength is a combined effect of fine η precipitates, dispersoids, solid solution elements, and fine grains.



Acknowledgements



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